

LAUNCHING OF FLAT PLATES WITH A SINGLE STAGE RECONNECTION GUN

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ABSTRACT

A magnetic coil with a square air core was constructed to launch metal plates edge-on. The final velocities of aluminum plates that differ in thickness were measured by using break wires. In addition, the position of an aluminum plate was determined by optical means as it was being launched. These results were compared to the predictions of a simple mathematical model.

INTRODUCTION

The launching of flat plates along a direction normal to the plane of the plate, using explosive charges to accelerate the plate, is a well understood and highly developed technique. Acceleration of flat plates along an axis parallel to the plane of the plate, however, is difficult using explosive charges. An electromagnetic launcher called the reconnection gun, invented by Cowan[1] and developed by Cowan and colleagues[2] at SNLA, provides an attractive option for plate launch in the edge-on orientation. In addition to obviating the need for high explosives, among the particular advantages of this type of electromagnetic launch are its contactless nature and relatively high efficiency for masses greater than a few hundred grams.

A single-stage reconnection-gun consisting of a square helical coil connected to a 11 kV, 100 kJ capacitor bank was assembled and used to accelerate, edge-on, a number of rectangular plates whose masses ranged from 96 to 396 grams. The final velocities of the plates were measured and compared with the values predicted by a simple mathematical model.

In this paper the design of the reconnection gun, the experimental results for a variety of plate masses, and a simple mathematical model of the acceleration process are described. The predictions of final plate velocity using the simple model are compared with measured values. We also briefly discuss future plans for the study of single-stage reconnection guns.

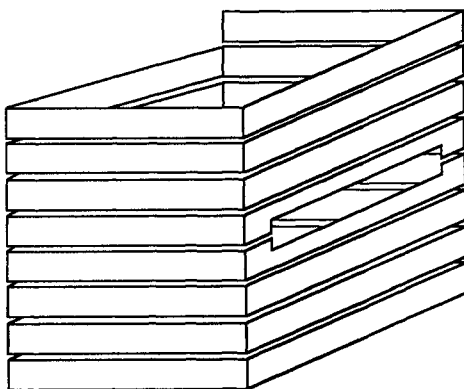


Fig. 1

EXPERIMENT

A coil, Fig. 1, was constructed from a 10x10 cm square aluminum box 23 cm long with 3 mm thick walls. The sides of the box were milled to form a square helical coil with 9 turns. The coil was confined on the outside by 5 cm of G10 fiber glass and on the inside by filling most of the core with fiber glass resin. The center part of the core was not filled so that the plate could be positioned inside the coil through a spacing between the windings. The coil inductance was 2.05 μ H with a plate in the core, and 2.73 μ H when there was no plate, giving an average inductance gradient of 6.8 μ H/m over the distance of 0.1 m. These inductances were measured at 2000 Hz which may take into account some of the skin depth effects. The coil was connected to a 1670 μ F capacitor bank by an Ignitron switch. For most of the work reported herein, the capacitor bank was operated without a crowbar circuit on the output which resulted in the circuit ringing at a frequency of 2200 Hz. The skin depth at this frequency is 1.7 mm for aluminum.

The final velocities for a set of aluminum plates that had thicknesses of 3.2 mm (approximately twice the skin depth of 1.7 mm), 6.4 mm, 9.5 mm, and 12.7 mm were measured as the initial energy of the capacitor bank was varied. The velocities were determined by the use of two break wires.

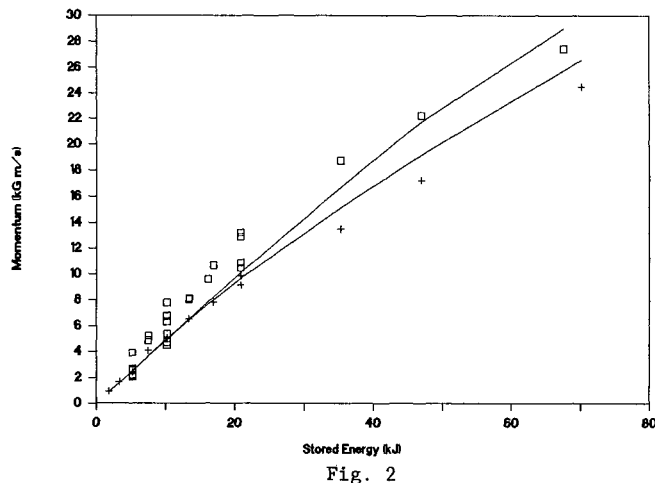


Fig. 2 shows the momenta of these plates as a function of the stored energy in the capacitor bank. The solid lines are a model calculation which assumes that the equation of motion is

$$a = G I^2(t) / 2M,$$

where "a" is the acceleration of the plate, G is the inductance gradient of the coil (6.8 μ H/m), M is the mass of the plate and I(t) is the current through the coil. For an underdamped circuit, the current is

$$I(t) = V_0 / \omega L \exp(-R/2L t) \sin(\omega t),$$

where

$$\omega = (1/LC - R^2/4L^2)^{1/2},$$

R is the equivalent resistance of the circuit, L is the total inductance, C is the capacitance of the bank (1670 μ F), and V₀ is the initial voltage of the capacitor bank. The equivalent resistance R and the total inductance L, 7.5 m Ω and 3.16 μ H, respectively, were found by fitting the above function to some of the measured currents and averaging the results.

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The equation of motion of the plate was integrated analytically, once to find the velocity as a function of time, and again to find the position as a function of time. These equations were used to find the time that the plate exits the coil, and the velocity of the plate at this time. This final velocity was then multiplied by the mass of the plate to give the momentum of the plate. The lower solid line represents the data for a 96 gram plate 3.3 mm thick, and the upper solid line is for the thicker plates that had masses ranging from 206 grams to 396 grams. The momentum of the 96 gram plate at all values for stored energy is lower, because the plate leaves the coil before the coil current decays, particularly at the higher capacitor bank energies. Thus the 96 gram plate did not receive the full impulse. The thicker plates, however, did receive the full impulse, because they exited after the coil current had decayed away. Since all the thicker plates received the same impulse for a given capacitor bank energy, they all had the same momentum and there is just one curve for all of the thicker plates.

EXP. & THEORY VELOCITIES

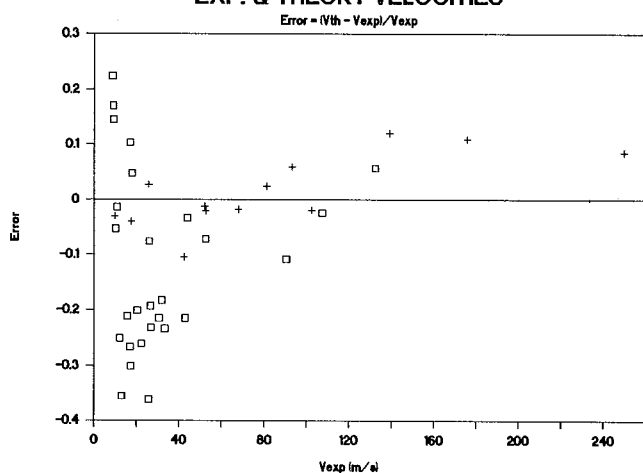


Fig. 3

Fig. 3 shows the error between the measured final velocities and the predicted final velocities for the 96 gram thin plate (crosses) and all the thicker plates (squares). Since the model which predicted the final velocities of the thin plate within 10% over the entire velocity range does not explicitly include skin depth effects, these effects are not evident in the data. Thus the model could be used to predict the final velocities of plates with thicknesses comparable to the skin depth, as well as the velocities of thicker plates.

The skin depth effect was evident, however, in the final plate velocities observed when the coil of the reconnection gun was driven by currents with different time profiles. For 21 kJ of stored energy the final velocity of the 238 gram plate was 21 m/s and 44 m/s when the coil was driven by an overdamped and underdamped current, respectively. The overdamped current was produced by connecting a crowbar switch in parallel with the coil. In this case, the current increased to a maximum as in the first quarter cycle of a sine wave and decayed exponentially after the crowbar switch was closed.

The Fourier transform of the underdamped current waveform shows a maximum at a high frequency whereas the transform for the overdamped case peaks at zero frequency. Thus the effective skin depths for these two cases are expected to be very different. This difference may explain why the final velocities of the plate are different in the two cases. The model predicts 60 m/s and 43.8 m/s for the final velocities of the plate for the overdamped and underdamped conditions, respectively. The experimental values are 21 m/s and 44 m/s, respectively. Thus, as expected, the model fails when the skin depth is large.

The induced currents in the plate will produce heating during the launch phase while the plate resides within the magnetic field. Because these currents have a nonuniform distribution within the plate and on the surface one expects a nonuniform surface temperature distribution immediately after launch. To provide additional insight into skin depth effects in the present experiments this surface temperature distribution was observed using an infrared video camera. A 133 gram plate was fabricated with a nose section capable of holding a nail oriented along the direction of plate motion. A plywood barrier was used to capture the plate in the proper orientation for viewing with the fixed IR camera immediately after launch. The infrared images showed that the top surface of the plate was heated along its trailing and side edges with the heated region extending inward about 0.5 cm from the edges. Little or no heating occurred in the middle of the plate, even though the thickness of the plate was about twice the skin depth. Thus the magnetic field was effectively excluded from the volume as though it were a thick plate. Therefore in our geometry, the thickness of a plate may not be the most important dimension to use to gauge the importance of skin depth effects. Plate length or plate width may be the more important indicator of these effects.

PLATE VELOCITY

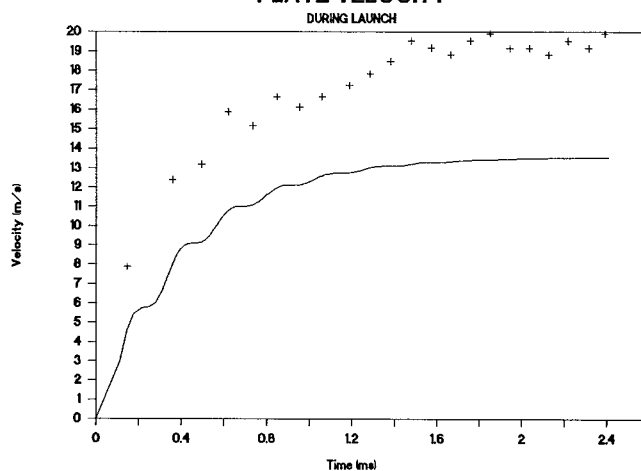


Fig. 4

The position of an aluminum plate during the launch was determined by optical means as another test of the model. This plate had two parallel rails in front that extended outside the coil. A clear plastic sheet with black bars printed on it was mounted across these rails. The time of interruption of a continuous, fixed, light beam by the black-bar array was recorded on a digital oscilloscope. Thus the position of the plate was recorded in time and the velocity of the plate can then be determined as the plate was being launched. Fig. 4 shows the experimental velocity as crosses, and the theoretical velocity as a solid line.

The model does not predict the final velocity very well in this particular instance, although the shapes of the theoretical and experimental curves are in good agreement. Fig. 3, however, indicates that the model may be used to predict the velocity and position of a plate as it is being launched at the higher final velocities.

CONCLUSION

A single-stage reconnection gun to accelerate flat metal plates to high velocities in a short distance has been constructed. A 96 gram plate was accelerated to a final velocity of 250 m/s in a distance of 10 cm, corresponding to an average acceleration of 32 kg. A simple mathematical model which does not explicitly include skin depth effects was used to predict the plate velocities. To provide data on skin depth effects plates with various thicknesses were launched. For plate velocities around 50 m/s and higher the model predicts velocities in reasonable agreement with the experimentally observed values although the discrepancy between theory and experiment is of order 30% or more at low plate velocities.

Infrared images of thin plates obtained immediately after launch showed that the plate was heated in a narrow region along the trailing edge and the side edges, where the magnetic field and induced current is large, but most of the plate area was not heated significantly.

The plate velocity during the launch phase was measured and compared with the model predictions. The shape of the predicted curve of plate velocity versus time agreed well with the experimentally observed trend although the magnitudes were not in close agreement at the relatively low plate velocity of the measurement, 19 m/s, a velocity dictated by the limited time response of the phototransistor used to detect plate movement. This limitation will be removed in future experiments by use of photodiode arrays with fast response times.

The overall trend of the measured plate velocity versus stored energy curve is in good agreement for the higher velocities. Currently the model is being used to predict the performance of a planned single-stage reconnection gun to launch heavier plates to higher velocities with higher overall efficiencies than realized in the current experiments.

[1] M. Cowan. PAT-APPL-7-034 354, Filed: 6 APR 87

[2] M. Cowan, E. C. Cnare, et al. "Proceedings of the 3rd Symposium on Electromagnetic Launch Technology, Austin, TX 1986", pp. 25-30, IEEE, Inc. New York, 1986